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PB-284 352

Municipal Wastewater Aquaculture

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Jun 78

United States
Environmental Protection
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Ada OK 74820

EPA-600/2-78-110
June 1978

Research and Development

PB 284 352

EPA

Municipal Wastewater Aquaculture

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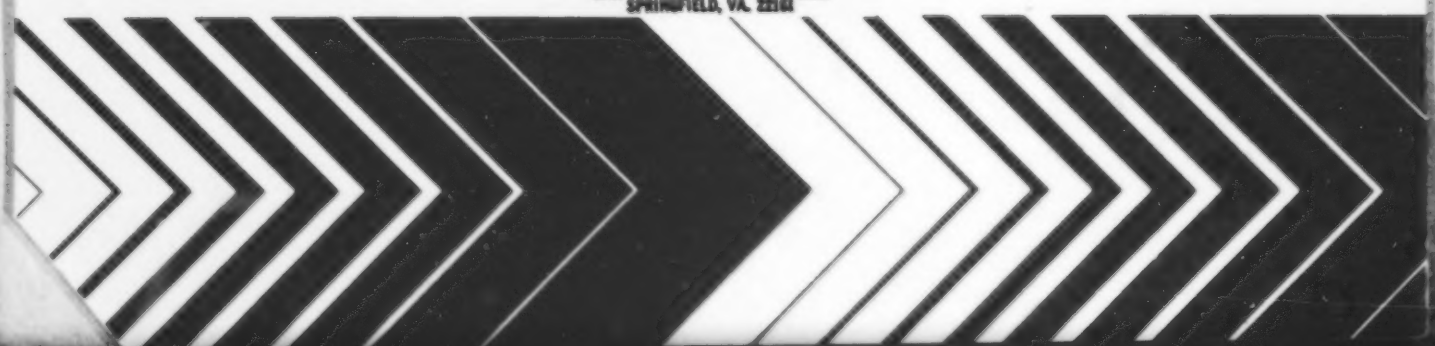

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-78-110		PB284352

4. TITLE AND SUBTITLE	5. REPORT DATE
Municipal Wastewater Aquaculture	June 1978 issuing date
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
William R. Duffer and James E. Moyer	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Robert S. Kerr Environmental Research Lab. - Ada, OK Office of Research and Development U.S. Environmental Protection Agency Ada, Oklahoma 74820	1BC611
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Same as above.	In-House
	14. SPONSORING AGENCY CODE
	EPA/600/15

15. SUPPLEMENTARY NOTES

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Fishes Aquaculture Wastewater treatment (municipal) Water Pollution Aquatic plants Invertebrates Fresh water Solids	Water reuse Wetlands Marine Microorganisms Organics Heavy metals Nutrients	68D

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	55
	20. SECURITY CLASS *(This page)*	22. PRICE
	UNCLASSIFIED	PC A04 MF A01

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE 1978—757-140/1304

EPA-600/2-78-110
June 1978

MUNICIPAL WASTEWATER AQUACULTURE

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FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the agency's effort involves the search for information about environmental problems, management techniques and new technologies through which optimum use of the nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate and management of pollutants in groundwater; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows; (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control or abate pollution from the petroleum refining and petrochemical industries; and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report contributes to the knowledge essential if the EPA is to meet the requirements of environmental laws that it establish and enforce pollution control standards which are reasonable, cost effective and provide adequate protection for the American public.

William C Galegar

William C. Galegar
Director
Robert S. Kerr Environmental Research Laboratory

ABSTRACT

The developmental status of the aquacultural alternative for treatment and reuse of municipal wastewater is reviewed. Major emphasis is given to the reduction or fate of pollutants in such areas as organics, solids, nutrients, heavy metals, residual hydrocarbons, and potentially pathogenic organisms. Economic assessments of treatment and production rates for organisms are included for several types of aquacultural processes. Aquacultural systems considered include natural wetlands, artificial wetlands, macrophytes, invertebrates, fish, and integrated or food chain units. The literature examined indicates that information available at this time is not adequate for design of operational aquaculture systems to treat or utilize inputs of municipal wastewater. Sufficient exploratory studies have been conducted, however, to demonstrate a definite potential for development of wastewater aquaculture systems. Areas having high potential for further research and development are identified. This report covers recent research progress in municipal wastewater aquaculture and was completed as of June 1977.

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SECTION 1

INTRODUCTION

Environmental problems associated with the disposal of wastewater are prompting the development of economical and reasonable treatment and reuse approaches in order to minimize the unnecessary expenditure of tax dollars and energy. The Federal Water Pollution Control Act of 1972 [PL 92-500 § 201 (d) (1)] requires that agricultural, aquacultural and silvicultural alternatives for wastewater reuse be evaluated and encouraged as treatment mechanisms.

The purpose of this report is to review the developmental status of the aquacultural alternative for treatment and reuse of municipal wastewater. Aquaculture is defined as the production of aquatic organisms under controlled conditions. The aquatic flora and fauna are included for both marine and freshwater systems.

Although the scope of this review is limited to municipal wastewater inputs into aquatic systems, aquacultural technology is also developing for industrial wastewater and non-wastewater sources. It should be noted that the same basic biological principles apply to all systems designed for the culture of aquatic organisms. Such factors as reproductive characteristics, life stage environmental requirements, feeding habits, and tolerance of high density populations must be taken into account in order to establish successful culturing procedures.

The major portion of technology developed for aquaculture has been oriented toward the production of human food items rather than treatment or reuse of wastewater. Bardach et al. (1) provide an excellent review of the developmental history, and current world-wide practices in aquaculture, but their consideration is limited only to those organisms which are cultured as human food.

According to the broad definition selected for aquaculture, conventional municipal wastewater treatment processes such as trickling filters, activated sludge, and sewage oxidation ponds could be included for review. We have, however, limited the scope to include only new or developmental processes rather than conventional or advanced application processes. For example, the aquacultural application which utilizes planktonic algae in combination with aerobic bacteria to oxidize organic wastes in sewage oxidation ponds is not included. Culture of higher food chain organisms, such as aquatic inverfebrates and fish which feed either directly or indirectly on unicellular forms, however, is included. Higher aquatic plants will also be considered since their culture is in the developmental phase. For natural systems, such as marshes and wetlands, the treatment effects of the overall population is examined with no distinction of the various food chain components.

SECTION 2

CONCLUSIONS

Aquaculture has been practiced for centuries in various parts of the world, and has been a significant source of food and fiber production in some countries. The application of waste materials to producing aquaculture systems for their fertilizer value has been a common practice through the years in some parts of the world. Only recently, however, has the use of designed aquaculture systems for treatment and management of municipal wastewaters been given serious consideration.

With the growing interest in aquaculture utilizing municipal wastewaters, there has been an increase in research activities in this area. This review of the current literature indicates that several different systems have been studied. These studies lack uniformity of approach and purpose; therefore, results are not easily compared and sometimes are conflicting or inconclusive.

Although there are many unanswered questions at this time regarding the use of designed aquaculture systems for municipal wastewater treatment and reuse, there are growing numbers of researchers, planners, and managers who believe that aquaculture has potential for development as an economical, simple, and effective alternative for municipal wastewater treatment and management. In addition, it is felt that, while offering an effective treatment alternative, aquaculture can yield a product of economic value to defray part of the operating costs. Another attractive feature is the potential energy savings of aquaculture wastewater treatment as compared to alternative systems. There are indications that some systems can, indeed, be energy producers by the conversion of a crop, such as water hyacinths, to a valuable fuel.

The overall conclusion of this study is that developmental research in municipal wastewater aquaculture is needed in order to establish reliable design criteria. Investigations to date indicate that the culture of several types of aquatic organisms have potential for development as an attractive alternative to conventional wastewater treatment systems from from the standpoints of both treatment effectiveness and economic feasibility. The following specific conclusions are offered to support the overall conclusion:

1. Exploratory efforts with the culture of water hyacinths for treatment of municipal wastewater has progressed more rapidly than those utilizing other organisms. Although the use of water hyacinths is limited geographically, research progress warrants a significant developmental effort oriented toward establishing design criteria.

2. Aquatic plants which are cosmopolitan under natural environmental conditions appear to have greater potential for wastewater treatment than those restricted in distribution due to temperature tolerance or other factors.

3. Wetland systems which could be established over a wide geographical area for freshwater and brackish water have great potential for developmental research in areas of wastewater treatment and utilization.

4. A large portion of research activity in aquaculture utilizing municipal wastewaters has emphasized production of organisms rather than treatment of wastewater. Research must be conducted to develop system design criteria related to process stability, costs and revenues, and treatment effectiveness.

5. Only a limited number of available organisms have been cultured experimentally using municipal wastewater. Of those studied, water hyacinth, seaweed, and midge larvae have demonstrated an impressive potential for production under conditions of wastewater culture.

6. Few exploratory tests have been conducted with supplemental feeding of aquatic animals or supplemental fertilizing of aquatic plants in municipal wastewater culture systems. Recycling of municipal wastewater utilizing supplementation should be investigated in order to determine the developmental potential for such practices.

7. Freshwater systems have a distinct advantage over marine systems for municipal wastewater treatment application. The advantage is due to the requirement for a much smaller volume of water which would result in a saving of equipment and/or space. Since wastewater effluents from municipal sources are more similar to freshwater than seawater, freshwater organisms may be cultured using non-diluted effluents, whereas marine systems require extensive seawater dilutions in order to maintain a favorable salinity range for the culture organisms.

8. Potential problems in the areas of disease transmission, health effects, and social acceptance pose a significant barrier to utilization of municipal wastewater products as food for humans. Developmental research for the present should concentrate on other product uses for organisms cultured in municipal wastewater.

9. Existing studies indicate that wastewater treatment by aquaculture may have its best application in combination with other methods of treatment. While revenues from the sale of aquacultural products may return a portion of the total construction and operation costs of such combined systems, income from product sales is usually insignificant compared to the overall expense of the system. In some cases, however, if comparisons of revenues and expenses are restricted only to the aquacultural component, a substantial net return for this component may be realized while providing additional wastewater treatment.

10. Reported water quality changes resulting from aquaculture systems vary widely with respect to type of system and mode of operation. Not considering differences in operation or other factors which would influence results, there is a wide variation in reporting of parameters for the same general type system. Probably more significant to this study are the serious omissions in data, lack of consistency in reporting, and comparability of information among the various researchers.

SECTION 3

RECOMMENDATIONS

Results of this review clearly indicate that man can recycle and treat wastewater by culturing aquatic organisms to simulate a portion of nature's activity. In this process, changes occur in the chemical, physical, and biological characteristics of the system. Unregulated changes are often detrimental to the system affecting such factors as survival, reproduction, and rates of growth. In those instances, however, where techniques have been developed for controlling inputs of food substances and nutrients and for regulating other critical environmental variables, an enriched aquatic system having high rates of production can be achieved. Municipal wastewaters contain highly valuable nutrient materials and are subject to management as aquatic systems for increased productivity.

Recommendations are oriented toward identifying appropriate culture organisms and developing the techniques required for regulating aquatic systems which receive inputs of municipal wastewater for purposes of treatment or recycling. The specific recommendations which follow are listed in priority order based on our opinion of the status of technological progress, present potential for research development of design criteria, and the exploratory effort needed to provide a technical base for future developmental research.

1. Additional developmental research with water hyacinth should be conducted to establish process design criteria for its natural geographical and climatic boundaries.

2. Consistent and uniform evaluation parameters should be adopted to allow comparison of results for different aquaculture systems and from different research projects.

3. Pilot-scale facilities with extensive control features should be utilized in developmental experiments to assure the research flexibility necessary for determining environmental tolerances, production rates, and changes in water quality associated with populations of test organisms.

4. Experiments with water hyacinth in a controlled environment should be conducted in order to evaluate extending the geographical and climatic areas of potential utilization.

5. Exploratory research should be conducted to determine the potential of aquatic macrophytes such as cattails, waterweeds, duckweeds, and bullrushes for utilization in development of municipal wastewater treatment processes.

6. Research should be conducted on utilization of artificial wetlands for wastewater treatment. Techniques for establishing and maintaining such areas, as well as wastewater pretreatment requirements and loading rates, should be determined.

7. Research to determine the value of natural wetlands systems for utilization of municipal wastewater should be expanded. Beneficial and detrimental effects of wastewater inputs must be determined in order to fully protect these systems.

8. Additional experiments should be conducted with organisms such as seaweed, midge larvae, and certain finfish species which have demonstrated a potential for increased production under conditions of wastewater culture.

9. Research into health effects associated with wastewater aquaculture should be pursued concurrently with research to develop treatment technology. Public acceptance of wastewater aquaculture will depend to a great extent on the proven safety, from a public health standpoint, of these systems. Delays in the implementation of aquaculture systems, shown to be technically feasible, can be largely avoided by early identification and resolution of health-related problems.

10. Studies to fully develop the economics of wastewater aquaculture should be conducted. Reliable cost data must be developed for construction, operation, and maintenance. These data should be correlated with treatment efficiencies in order that reliable cost effectiveness analyses may be performed, and fair comparisons made with other treatment alternatives. Data should be developed for revenues and other tangible benefits which could be produced from wastewater aquaculture.

11. As design criteria are developed for municipal wastewater aquaculture processes, research efforts should include a complete evaluation of energy requirements related to treatment efficiencies in order to allow a valid comparison with other types of systems. It appears that many wastewater aquaculture systems will offer significant energy savings due to efficiencies achieved by direct conversion of solar energy by aquatic plants.

SECTION 4

LITERATURE SURVEY

The literature search for this report has been limited to those aquacultural studies concerned with the treatment and reuse of municipal wastewaters; moreover, it has been confined primarily to those investigations of a current and more recent nature. While ancillary data, such as production rates, have been included in some instances, major emphasis has been given to the reduction or fate of pollutants in the following areas of interest: organics, BOD, COD, and others; solids; nutrients, principally nitrogen and phosphorus compounds; heavy metals; residual hydrocarbons, such as petroleum and pesticide wastes; and biologicals, those bacteria and viruses of a potentially pathogenic nature. Economic assessments are also reported for some types of aquacultural processes. For purposes of organization, this section of the report has been arbitrarily divided into categories to include a consideration of natural wetlands, artificial wetlands, macrophytes, invertebrates, fish, integrated systems, and economic evaluation.

NATURAL WETLANDS

Wetlands, both marine and freshwater, have inadvertently served man as natural waste treatment systems for centuries; only in more recent years, however, have these areas received significant attention as valuable resources for degrading man's contaminants.

In an excellent review article, Valiela, Vince, and Teal (2) point out that vegetated wetlands act as invaluable natural sinks for wastes by providing areas for sedimentation and/or adsorption of particulate matter and a reducing environment for the conversion of dissolved heavy metals into insoluble sulfides. Additionally, denitrification is enhanced by the presence of microorganisms in the soil substrate. Plant species present in wetlands readily assimilate dissolved inorganic nutrients, principally nitrogen and phosphorus compounds, and convert these substances into plant tissue, thereby limiting accessibility of the chemicals.

The authors state that the predominating plant species colonizing wetlands are tolerant to a wide variety of environmental stresses, rapidly colonize open areas, and possess other adaptive mechanisms that allow them to persist in a changing chemical environment. This wide diversity of plant species has allowed wetland vegetation to survive the added stresses of processing waste effluents up to as yet unspecified limits.

In a study of the Brillion marsh located 15 miles below the sewage treatment plant outfall for the city of Brillion in Calumet County, Wisconsin, Spangler et al.

(3) noted a dramatic decrease in BOD_5 (80.1%) and a significant decrease in COD (43.7%). A decrease in suspended solids (29.1%) was accompanied by an increase in dissolved solids (34.0%) which resulted in a net increase of 8.5% in total solids.

Of the plant nutrients present in municipal wastewaters and sludges, the macronutrients, phosphorus and nitrogen, have been studied more extensively by investigators conducting wetland studies due to the essential nature of these elements for plant growth.

Valiela et al. (2) found that the addition of phosphate had no effect on the growth of higher plants in saltwater marshes exposed to tidal flooding. This lack of response by macrophytes was believed to be due to the presence of large amounts of previously deposited seawater-borne phosphate in the fine sediments of the marsh. In the Brillion marsh study (3) mentioned previously, similar results were noted when a mass balance study of total phosphorus, using estimated streamflow data and average phosphorus concentrations, revealed the same order of magnitude of phosphorus leaving the marsh as entering it. Harvesting proved not to be a practical method for the removal of substantial amounts of phosphorus, as marshes remove phosphorus in the growing season but release it at other times.

Since the addition of phosphate showed no effect on the growth of higher plants in saltwater marshes, Valeila and co-workers (2) have attributed the growth-enhancing properties of sewage sludge to the presence of nitrogen. Following experimental enrichment of a marsh with sewage sludge, two- to threefold increases in the production of higher plants were obtained. In another study (4) of a brackish marsh in New Jersey dominated by Phragmites communis, the investigators determined the amount of nitrogen accumulated by the marsh to be approximately five times the amount contributed by an upstream sewage treatment plant, even after years of operation.

Valeila et al. (2) state that the amount of sewage nutrient capable of being processed through wetland vegetation is far greater than that present in the standing crop, since the vegetation of a wetland is constantly growing and dying. Harvesting and analysis of above-ground part plants may not present a true picture of the extent of nutrient removal from sewage application due to the seasonal transport of these elements between above-ground and below-ground plant parts; additionally, leaching by the plants of both nitrogen- and phosphorus-containing compounds may be of significance.

Another process to be considered in the amount of sewage nutrients that may be processed by wetlands is denitrification by microorganisms present in the anoxic layers. By means of this process and storage through growth, algae and bacteria are able to absorb and dispose of a substantial amount of water-borne nitrogen.

In a study of a freshwater tidal marsh (Hamiltion marshes) located in the Delaware River Basin, Whigham and Simpson (5) concluded that the high marsh areas functioned as sinks for nitrogen and phosphorus during the summer months,

and then slowly released these elements back to the low marsh areas during the fall and winter, following plant die-off. Greij (6), studying nitrogen concentrations of the Macatawa River in Michigan below a sewage outfall, found that NO_3^- nitrogen levels decreased 41.8% from the main current of the river to just inside a cattail stand of the marsh.

In regard to metal uptake and release by wetlands, Valeila et al. (2) have stated that this characteristic is dependent upon a number of factors, including presence of organic matter, distance from the source, salinity, temperature, pH, the metal element, and sediment type and size. Heavy metals, especially lead, zinc, and cadmium, are present in large amounts in sewage sludges and leachates from sanitary landfills. One study by these investigators of marsh sediments at increasing distances from a landfill operation revealed that the concentrations of lead, zinc, and cadmium were rapidly diminished, the lead being converted to insoluble sulfides while zinc and cadmium were taken up into the marsh sediments via adsorption and ion exchange processes. Such results indicate that wetlands provide good sinks for excess heavy metals; however, the marshes do not serve as permanent sinks such as those found in deep sedimentary deposits. The reason is that certain plant species can undergo physiological adaptation that allow their root systems to penetrate the sediment of the anoxic zone and assimilate heavy metals. More important than the plant life present in wetlands for the retention of heavy metals is the organic content of the sediment. The lead concentration of the more organic sediments was found to be about four times more than sediments from dredge spoil operations (7).

Most of the losses of zinc and cadmium from wetlands are believed to be through routes other than plant decay and dead grass exports since only a small percentage of these metals is taken up by the vegetation present. Shellfish have been suggested as a source for the removal of metals from wetlands receiving municipal wastes containing elevated metal concentrations. It is generally believed, however, that the largest majority of metals are flushed from marshes by tidal action (2).

Information regarding the fate of organic hydrocarbons in wetlands is extremely limited (2). The presence of fine muds should provide a surface for the adsorption of hydrocarbon products, such as petroleum and pesticides, due to their relatively low solubilities in water. One study (2) reported a 10^5-fold concentration of chlorinated hydrocarbons on muds as compared to that found in sea water. In a study (2) conducted of a sanitary landfill, polychlorinated biphenyls in the leachate were found to be greatest at the source of contamination and rapidly diminished thereafter.

Despite relatively low water solubility, hydrocarbons may leach out into surrounding waters or be structurally altered by exposure or microbial oxidation. In one study by Krebs et al. (8), a substantial amount of aldrin was microbially oxidized to dieldrin. Petroleum hydrocarbons are known to be degraded by weathering, leaving complex residues of organic substances (2). Another factor to be considered in the degradation of hydrocarbons by wetlands is actual uptake and metabolism of the compounds by the plants themselves; e.g., Seidel (9) has isolated and developed a number of plant species that are capable of cleaving hydrocarbons and metabolizing the end products to amino acids for incorporation into protein.

The effect of passage through a moderately saline marsh field on the survival of enteric indicator microorganisms was studied by Valeila et al. (2). Their studies showed that the numbers of total and fecal coliforms were halved by residence over the marsh during tidal inundation. Spangler et al. (3), in studies on the Brillion Marsh in Wisconsin, found that the total coliform count of the wastewater was reduced 86.2% following freshwater marsh treatment.

In another series of investigations designed to utilize natural wetlands for the recycle of treated municipal wastewaters, researchers from the University of Florida (10) are discharging secondarily treated effluent into cypress domes at the rate of one inch per week. Results from the project have indicated the BOD_5, total nitrogen and total phosphorus levels in the dome surface waters consistently exceeded standards recommended by the State of Florida for wastes receiving tertiary treatment. The cypress dome disposal method, however, has been concluded to be more efficacious from the standpoint of conserving and improving water quality than other more conventional treatment methods--groundwater injection, overland spreading, or direct release to marine and freshwater environments.

Kadlec and Kadlec (11) have conducted similar experimentation involving the disposal of 100,000 gal/day of secondarily treated sewage effluent to a peat bog marsh area located in the Houghton Lake Wildlife Research Area of Michigan. The net effect of two seasons of pumping into a 10-acre sector appear to be insignificant. According to the investigators, "no adverse effects" on the ecology of the peat bog have been noted when compared to the control areas.

ARTIFICIAL WETLANDS

As the value of wetlands in processing wastes has become increasingly evident, attempts have been made by investigators to construct artificial systems that duplicate those waste treatment functions provided by natural wetlands.

In a study of an experimental ditch planted in rushes (Scirpus lacustris) and reeds (Phragmites australis), DeJong (12) established that the plants contributed to sewage purification not only through the incorporation of nutrients into plant tissue, but also by serving as points of attachment for sewage-purifying microorganisms. The study was conducted during the summer months at a camping site in the Netherlands, and the experimental ditch occupied a land area of one hectare (2.47 acres) at a depth of 0.4 meter. Dramatic decreases in the mean BOD_5^{20} from 257 mg/l to 11 mg/l (95.7%) and COD from 530 mg/l to 70 mg/l (86.8%) were recorded following ten days' detention. Small and co-workers (13) in a study at Brookhaven National Laboratory of a 0.2 acre each marsh/pond system treated with various blends of pre-aerated raw sewage/septage feed, also noted significant reductions in the average concentrations of these two parameters over a thirteen-month study period--BOD_5 from 148 mg/l to 30 mg/l (79.7%); COD from 427 mg/l to 56 mg/l (86.9%). Utilizing a series of experimental and control basins lined with PVC and layers of sand and coarse gravel, Spangler et al. (3) were able to demonstrate that the basin planted in softstem bulrush (Scirpus validus) was able to remove 91% of the BOD and 61% of the COD after only five hours' detention.

Solids data concerning the various artificial wetlands systems are sparse; however, the following average solids reductions (mg/l) were reported for the study (13) conducted at Brookhaven National Laboratory: total solids, 548 to 205 (62.6%); total volatile solids, 305 to 100 (67.2%); suspended solids, 331 to 43 (87.0%); volatile suspended solids, 212 to 34 (84.0%); total dissolved solids, 203 to 164 (19.2%).

The data available concerning the uptake of phosphorus compounds by natural and artificial wetlands appear somewhat anomalous. As mentioned previously, Valiela et al. (14) have found that the addition of phosphate to salt marshes exposed to tidal flooding had no effect on higher plant primary production; however, when added to experimental salt marsh plots, 91-94% was removed. Similarly, while studies (3) of the Brillion marsh revealed no overall removal of phosphate, essentially 100% retention was obtained when phosphate compounds were added to experimental basins. Other studies of artificial wetlands, notably by DeJong (12) and Small (13) have shown significant phosphate uptake by these systems. Whether the failure of natural systems to remove phosphate compounds from wastewaters is the result of a condition of long-term saturation, or due to the absence of other necessary growth factors remains a matter of conjecture.

Nitrogen uptake by experimental salt marsh plots has been found to be in the range of 80-94% by Valiela and co-workers (14). DeJong (12), utilizing a pond planted in rushes, obtained over 90% nitrogen removal following ten days' detention. Sixty percent reduction of total nitrogen was measured by Small and others (13) in their marsh/pond studies. No major qualitative changes in predominant plant species were noted over a five-year period by Valiela et al. (15), despite two- to threefold increases in plant growth following nitrogen fertilization. Teal (16) points out that wetland vegetation does not act as a permanent sink for nutrients. In studies of artificial salt marshes, approximately 12% of the added nitrogen could be accounted for in above-ground growth. Following senescence of the grass sward, it was estimated that 6% of the added nitrogen was lost as dead organic matter.

Other important biological processes to be considered in the utilization of nitrogen by wetlands include denitrification and nitrogen fixation by microorganisms. Following addition of combined nitrogen forms to experimental salt marshes, a reduction in nitrogen fixation was observed (2,17); the microorganisms preferentially utilized the added combined nitrogen rather than performing the energy-requiring process of fixation.

The uptake of metals by experimental salt water marsh plots fertilized with sewage sludge has been studied by Valiela (2) and his associates to determine the extent that vegetation contributes to metal export. Nearly all the lead added in sludge fertilizer was retained by the marsh surface sediments, and the lead content of the marsh grasses increased from 2.3 to 4.8 ppm. The greater absolute loss of lead from the fertilized plots as opposed to the control plots through tidal export was attributed to the increased lead content and the greater biomass of grass produced by the fertilized plots (15,16,18). Only minimal amounts, 2-3%, of the added zinc was lost through the export of dead grass (2); 16% was believed lost through the export of dissolved zinc compounds. Cadmium exhibited an even lesser retention than zinc in the fertilized plots, with 66% leaving other than by grass export.

In a subsequent report by Valiela and Vince (19) of low marsh and high marsh experimental saltwater plots in which metals were provided by the addition of a sewage-sludge based fertilizer, the following percentage reductions were observed as having been retained by the marsh:

Percentage of Added Metal Retained by Marsh

Metal	Low Marsh	High Marsh
Copper	60	100
Iron	80	100
Lead	55	100
Manganese	55	60
Nickel	45	65
Zinc	20	45
Cadmium	20	35
Chromium	20	50

While it is obvious that the high marsh experimental plots were more effective in retaining metals, the authors offer no explanation of this apparent anomaly except to state that the plots were dominantly populated by different plant species.

Small (13), in the thirteen-month study of the marsh/pond system conducted at Brookhaven National Laboratory, reported the following average metal reductions between the sewage influent and effluent water of the system: chromium-80%, copper-96%, iron-68%, manganese-97%, and zinc-86%. While initial concentrations of these metals were not overly high, it is obvious that the marsh/ pond system was extremely effective in removing metals from sewage wastewaters.

An additional factor to be considered in the removal of metals from wastewaters by plants is the plant's ability to adapt to growth in the presence of greatly increased concentrations of metals. Not only are plants capable of adapting to growth in media containing levels of metals that would be toxic to non-adapted species, but these plants are able to assimilate the greater concentrations into plant tissue. Dr. Käthe Seidel and co-workers (20) at the Max Planck Institute in Germany have shown that the metal absorption capacity of the bulrush, Schoenoplectus lacustris, varies with the environment in which it is grown. For example, in healthy lake water this plant absorbs 18 ppm (parts per million) copper; whereas, in sewage adsorption is 50 ppm, an increase of 2.8 times. For other metals, the increase is even greater--cobalt, 3 ppm in lake water as opposed to 15 ppm in sewage, a fivefold increase; manganese, 260 to 2500, a 9.6-fold increase; chromium, 2.5 to 115.0, a 46-fold increase; nickel, 3.5 to 30.0, an 8.6-fold increase; and vanadium, 6 to 115, a 19.2-fold increase.

As stated previously, information regarding the decomposition of hydrocarbons in wetlands is limited. Valeila et al. (2) found circumstantial evidence for the lack of movement of chlorinated hydrocarbons in their experimental studies of salt marshes. While fiddler crabs exhibited harmful effects from exposure to chlorinated pesticides present in applied sewage, the effect was absent two meters downstream from the experimental site.

Seidel's (20) experimental work with bulrushes proved that these plants are capable of cleaving the aromatic ring of phenol and subsequently utilizing the end products in their metabolism. Other hydrocarbons for which these investigators have obtained varying degrees of success utilizing treatment by marsh plants include pentachlorophenol and cyanogen.

That seawater has a bactericidal effect on enteric bacteria has long been established; however, no information was found in the literature regarding survival of these organisms in artificial marine wetland situations. DeJong (12), in his studies of experimental ditches planted in rushes and reeds, obtained highly significant average reductions of 99.9% in the most probable number (MPN/ml) of bacteria utilizing a 10-day detention time. Employing secondary activated sludge effluent as a feed, Spangler (3) was able to obtain reductions of 90-99.7% in coliform bacteria following only 5-hour detention periods in an experimental pond populated with softstem bulrush (Scirpus validus). Although reductions in the numbers of potentially pathogenic microorganisms by passage through wetlands is extremely good, and probably better than for either the trickling filter or activated sludge treatment systems (12), nevertheless, there remains the possibility of a disease outbreak from this source.

MACROPHYTES

Although a number of aquatic macrophytes, including alligator weed, duckweed, and submersed vascular plants have been studied for the reclamation of wastewaters, by far the greatest emphasis has been placed on the utilization of water hyacinths.

Water hyacinth, Eichhornia crassipes (Marts.) Solms, is a native of South America. Introduced into the United States in 1884, the species spread rapidly and became established in waterways of several southern states. Due to rapid growth, problems such as obstruction of water flow and water loss through transpiration resulted. Weed control programs were initiated in 1899; early control measures involved mechanical procedures later replaced by the use of herbicides. Holm, Weldon, and Blackburn (21) estimated a loss of $43 million in the southeastern United States during 1956 despite extensive control efforts.

Water hyacinths are widely distributed in the tropical and subtropical regions of the world. Generally, the geographical area in which water hyacinths thrive is bounded by 32° N and 32° S latitude. One of the fastest growing of aquatic macrophytes, the number of water hyacinth plants doubles every 10 to 15 days under favorable conditions. Penfound and Earle (22) have reported water hyacinth mats having densities of 125 to 184 tons per acre. Growth studies reported by Wolverton and McDonald (23) indicate that one acre can produce 800 to 1,600 pounds of water hyacinth per day.

Waste water treatment systems, utilizing water hyacinths, have been proposed for the removal or degradation of nutrients, organic materials, trace metals, solids, and microorganisms. Robinson et al. (24) discuss design of systems with respect to hyacinth growth rates and degrees of nutrient removal required. For tertiary treatment they estimate that 31 to 156 acres would be required for a throughput of 1 mgd at an annual production rate of 20 tons/acre. Participants

of an EPCOT Technology meeting at Walt Disney World in Florida (25) concluded that about 15 acres of water hyacinths could process 1 mgd of municipal wastewater. A plan was developed to design a water hyacinth system for the tertiary treatment of sewage coupled with the production of useful products from the biomass. A variety of uses have been evaluated for harvested water hyacinths, including animal feed, compost, fertilizer, paper products, conversion to methane, and alcohol production. Based on a study to evaluate the economics and processing of water hyacinth products for cattle feeding, paper-making, and compost, Bagnell et al. (26) indicate that compost may be the best use, since this product had the highest value with the lowest processing cost. In tests involving anaerobic fermentation of water hyacinth, Wolverton, McDonald, and Gordon (27) found that the biogas produced contained a high percentage of methane. At an incubation temperature of 36° C, non-contaminated plants yielded 8.9 ml methane per gram wet weight, while nickel-cadmium contaminated plants yielded 11.3 ml methane per gram wet weight. Methane content of the total bio-gas produced was 69.2% and 91.1%, respectively.

In the study of a drainage canal receiving municipal effluent from the Gregory, Texas Wastewater Treatment Plant, Dinges (28) noted a mean reduction in BOD_5 of 35.4%. The canal surface area was 1.2 acres with a throughput of 140,000 gallons per day. Dinges (29) found that the mean BOD and COD decreased dramatically through a pilot system composed primarily of water hyacinth pond units receiving stabilization pond effluent from the Williamson Creek Waste Water Treatment Plant at Austin, Texas. The pilot system, occupying a surface area of 0.14 acres with a detention time of about 5 days, yielded mean reductions in BOD_5 from 19 mg/l to 3.5 mg/l, BOD_{10} from 108 mg/l to 20 mg/l, soluble BOD_5 from 8.1 mg/l to 2.2 mg/l, COD from 82 mg/l to 32 mg/l, soluble COD from 55 mg/l to 30 mg/l and TOC from 15.3 mg/l to 9.8 mg/l.

In laboratory scale investigations Wolverton, Barlow, and McDonald (30) found that the BOD_5 of raw sewage was reduced 97% utilizing water hyacinths compared to 61% for the plant-free control and the BOD_5 of secondary effluent was reduced 77% compared with 6% for the control following 7 days exposure. An experimental hyacinth lagoon at Orange Grove, Mississippi, studied by Wolverton and McDonald (31,32) for a period of one year, showed a reduction in BOD_5 for varied rates of flow. The hyacinth lagoon which received effluent from an aerated primary and secondary lagoon series had a surface area of 0.28 hectares and a volume of 6.8 million liters. During two months operation at a flow of 437,000 liters/day, a BOD_5 reduction of 75% and a TOC reduction of 31% was noted. Operation for four months at 870,000 liters/day resulted in a 79% reduction of BOD_5 and a 26% reduction of TOC. Four months at 1,059,000 liters/ day resulted in a 66% reduction in BOD_5 and a 25% reduction in TOC. Reductions in BOD_5 of 60% and TOC of 34% were noted for two months of operation at a flow of 1,892,500 liters/day.

Wolverton and McDonald (31,33) evaluated a single cell sewage lagoon located at Bay St. Louis, Mississippi, in terms of utilizing water hyacinth to upgrade the effluent. The lagoon had a surface area of 17.5 hectares and a domestic wastewater influent of about 3.8 million liters/day. An enclosed area of 2.5 hectares around the point of discharge contained water hyacinth. Over a four-month period, a 60% reduction in BOD_5 occurred from 39 mg/l to 16 mg/l.

Dinges (28) found that total dissolved solids reduction was 59.3% for an expanding water hyacinth population in a drainage canal at Gregory, Texas. The mean total suspended solids for the pilot unit at the Williamson Creek Treatment Plant (29) decreased from 46 mg/l in the influent to 7.1 mg/l in the effluent and mean volatile suspended solids decreased from 40 mg/l to 5.2 mg/l.

In laboratory scale tests utilizing water hyacinths at the National Space Technology Laboratories (NSTL), Wolverton, Barlow, and McDonald (30) found that total suspended solids were reduced 75% compared to 15% for the plant-free control following a 14-day exposure period. Wolverton and McDonald (31) found reduction of 71% in total suspended solids at Orange Grove, Mississippi from a yearly average influent level of 49 mg/l to 14 mg/l. A reduction of 14% occurred in total dissolved solids, the average influent level of 244 mg/l being reduced to an average of 210 in the effluent. In the sewage lagoon at Bay St. Louis, Mississippi (32,33), total suspended solids were reduced 88% from 125 mg/l to 15 mg/l.

The water hyacinth population in a drainage canal receiving effluent from the wastewater treatment plant at Gregory, Texas (28), reduced nitrate from 7.24 mg/l to 4.06 mg/l (43.9%) and phosphate from 16.4 mg/l to 4.3 mg/l (73.6%). The Williamson Creek pilot pond (29) also decreased nutrient concentrations: mean level of ammonia was reduced from 2.1 mg/l to 0.6 mg/l, total organic nitrogen from 4.3 mg/l to 1.2 mg/l, and phosphate from 15.4 mg/l to 10.6 mg/l.

Reductions in nitrogen and phosphorus were noted in NSTL (30) laboratory scale tests. In a 7-day exposure to raw sewage, the hyacinths removed 92% of the total Kjeldahl nitrogen compared to 18% for the plant-free control and 60% of the total phosphorus compared to 13% for the control. A water hyacinth-covered lagoon at Orange Grove, Mississippi (31), reduced total Kjeldahl nitrogen by 47% and total phosphorus by 11%.

Ornes and Sutton (34) found that available phosphorus in static effluent from an activated sludge treatment system was significantly reduced by water hyacinths. After one week the available phosphorus decreased from 1.42 mg/l to 0.97 mg/l (32%); following two weeks exposure, the level was 0.41 mg/l or a 71% decrease from the initial concentration. In a related study (35) utilizing duckweed, these investigators obtained over a 90% reduction in the phosphorus content of sewage effluent after the first four weeks of an eight-week test period. For the entire eight-week study period, phosphorus removal was 97%. McNabb (36), studying an aerobic pond populated principally by submersed flora (Potamogeton foliosus, Elodea canadensis, and Ceratophyllum demersum), estimated that with controlled harvesting, 20-25% of the total phosphorus input and 50-70% of the total nitrogen input would be removed at a detention time of 28 days during the growing season.

Several laboratory scale experiments utilizing water hyacinth have been conducted involving the uptake of heavy metals from static water systems. Wolverton and McDonald (37) found that up to 0.176 mg of lead and 0.150 mg of mercury was removed per gram of dry plant material in a 24-hour period. Wolverton (38) reported removal of up to 0.67 mg of cadmium and 0.50 mg of nickel per gram of dry weight of water hyacinth for a 24-hour exposure period. Related removal figures for alligator weeds were 0.101 mg of lead after 24 hours and 0.153 mg of mercury after a 6-hour exposure period. Wolverton and McDonald (39) noted

that 0.439 mg of silver, 0.568 mg of cobalt, and 0.544 mg of strontium was removed from solution per gram of dry weight of water hyacinth for a 24-hour exposure period. Comparable values for alligator weeds were silver, 0.439 gm; cobalt, 0.130; and strontium, 0.161 mg. Sutton and Blackburn (40) found that increasing the concentration of copper sulfate pentahydrate (CSP) resulted in an almost linear increase of the copper content of the roots of water hyacinths. At a concentration of 0.25 ppm of copper in the treatment solution, the copper content of the plant roots was 41 ppm. With an increase in concentration of the treatment solution to 16 ppm, the content of the roots increased to 14,801 ppm.

Based on laboratory experiments, Wolverton, Barlow, and McDonald (30) estimated that water hyacinths had the potential to remove 0.61 kg of cadmium, 0.042 kg of lead, 0.036 kg of mercury, and 0.12 kg of nickel per acre per day provided mature plants were harvested every 24 hours.

Wolverton and McKown (41), in static water studies, found that 36 mg of phenol was removed in 72 hours per gram dry weight of water hyacinth. Estimates were that water hyacinths had the potential for removing 160 kg of phenol/ hectare in a 72-hour period.

In related studies, these investigators (32) noted that water hyacinths were not effective in the removal of fecal coliform bacteria from sewage effluent. At the Williamson Creek Pilot System, however, Dinges (29) found that fecal coliform concentrations were reduced from a mean of 2,536 per 100 ml in the influent to a mean of 98 per 100 ml in the effluent.

INVERTEBRATES

A variety of animal organisms that feed directly on phytoplankton cultured in ponds receiving municipal wastewaters has been studied in an effort to develop a biological method for the clarification and purification of these waste effluents while concurrently producing a byproduct of economic value. Organisms being considered include Daphnia and related species (water fleas), Artemia (brine shrimp), and assorted bivalve mollusks (oysters, clams, and mussels).

In a series of studies conducted on an experimental Daphnia culture unit receiving effluent from a waste stabilization pond, Dinges (28,42,43) found mean BOD_5 reductions to be 69% and 79%, while COD values were reduced 67% and 55%. Detention time for these studies was 11 days with a BOD_5 loading rate of 35 to 44 pounds/acre/day. Volatile suspended solids decreased 83-86% during the experimental periods. At a Daphnia population density of 2,000 organisms per liter, Frook (44) obtained an 80% reduction in suspended solids within 100 minutes.

Trieff, et al. (45), in a static laboratory study culturing the marine algae Tetraselmis in wastewaters for use as a food source for brine shrimp, found significant decreases following feeding in the overall values for BOD_5 and suspended solids from 318 to 23 mg/l (93.0%) and 120-20 mg/l (83%), respectively. An additional algae stage was employed to further reduce these values.

As regards the utilization of soluble nutrients in the Daphnia culture unit, Dinges (43) makes the following comment: "Soluble nutrient minerals were not removed in passage through the culture unit. Phosphate levels remained about the same, and nitrates and organic-bound iron increased." Nutrient values reported by Trieff (45) indicate that following the feeding of Tetraselmis algae to Artemia, effluent levels for phosphate and nitrate were reduced from 20 to 10 mg/l (50.0%) and from 30 to 7 mg/l (77%) below the amounts originally measured in the raw sewage culture medium.

While no reports were found on the effects of metals on Daphnia or brine shrimp, mollusks are known to accumulate heavy metals present in the environment. Clams and oysters, placed in creeks that drained plots fertilized with sewage sludge, contained significantly higher concentrations of cadmium, but not lead or zinc (2). Hence, the investigators assumed that more cadmium than zinc or lead was flushed from the fertilized marsh plots. No appreciable differences in the amount of growth or percent survival of the oysters and clams was noted, however.

Domestic wastewaters are known to contain elevated concentrations of metals due to various treatment control procedures and additions from household products. Kerfoot and Jacobs (46), culturing oysters on phytoplankton grown in a 1:4 mixture of domestic effluent-filtered seawater, found that metal concentrations of zinc, copper, cadmium, chromium, lead, and nickel declined in the cultured oysters after the 45th day of a 102-day test. They attributed the lack of metal accumulation to dilution of the effluent by seawater and the increased growth of the oysters, with dilution effects being primarily responsible. It was concluded that oysters may be propagated in a wastewater-seawater medium without raising the danger of metal contamination.

In a related study employing the same effluent-seawater ratios containing deliberately elevated concentrations of the previously mentioned metals, Kerfoot and Redmann (47) observed that, in general, a concomitant rise in the content of these metals in the oyster tissue also occurred. Of the six metals, lead showed the more abrupt rise. From these studies the authors were able to formulate a series of permissible levels for each metal in the following categories: algae, shellfish, human acute, human chronic, and pollution alert. A final suggested guideline of permissible levels was offered, encompassing all categories.

The retention and survival of pathogenic and potentially pathogenic bacteria and viruses following passage through invertebrate waste treatment systems have been studied. Dinges (42,43) reported reductions of 72.1% for total coliforms and 98.7% for fecal coliforms in the effluent from the Daphnia culture ponds. In the saline effluent resulting from brine shrimp culture, Trieff (45) obtained 99.9% reductions for both coliforms and enterococci. No enterococci and an insignificant number of coliforms--3.7 per 100 Artemia organisms--were isolated from tissue specimens, but were assumed to be associated with the algae present in the gut of the brine shrimp.

In a comprehensive series of studies conducted at the Woods Hole Environmental Research Laboratory, Metcalf (48) found that not only enteric viruses present naturally in sewage, but also exogenously added viruses, including polio, were

taken up and retained by both juvenile and adult oysters. Depuration efforts were successful in most instances; however, on rare occasions virus was recovered from shellfish tissue after 6 days. The author concluded that in its present state of development, the production of shellfish for human consumption from domestic waste effluents is not feasible from a public health standpoint.

FISH

Three approaches have been explored for the culture of fish utilizing municipal sewage: 1) fish stocking directly into sewage lagoons; 2) addition of sewage effluent to fish ponds; and 3) conversion of sewage into lower food chain organisms, such as algae and microinvertebrates prior to discharging into fish ponds. Tsai (49) provides an excellent review of these approaches as well as an assessment of the merits of each.

The majority of experiments reported, involving the use of sewage for the culture of fish, have been oriented toward evaluating the suitability of sewage as a culture medium and establishing rates of fish production. Low levels of dissolved oxygen, susceptibility to disease, water property changes, and presence of toxic materials are among the technical problem areas that have been noted for culture of fish utilizing sewage. There is little question, however, as to the nutritional value of municipal sewage for the culture of fish (50). In sewage ponds owned by the Bavarian Power Company at Munich, Germany, 500 kilograms of carp, Cyprinus carpio, was produced per hectare/year with a slow exchange of water. In a rapidly flowing stream having a high sewage content in West Java, carp confined to bamboo cages yielded 50 or more kilograms per square meter of cage surface or 500 metric tons per hectare.

Tsai (49), in a discussion of the use of fish ponds for sewage purification, indicates that the ponds have proved very satisfactory in many instances as an advanced sewage treatment process. Kisskalt and Ilzhofer (51) found that effluents from fish ponds had oxidizability values only slightly greater than those of natural waters and that the disposal of such wastewaters presented no difficulties. Fathead minnows were successfully cultured in a sewage stabilization system by Trimberger (52). The system consisted of five oxidation ponds operated in a series. Initially stocked at one pound per acre, subsequent harvesting after six months yielded 378 pounds of minnows per acre. A decrease in turbidity was also noted for the minnow-stocked ponds.

Several species of fish were stocked by Coleman et al. (53) in the last four cells of a sewage oxidation pond system at the Quail Creek Plant located northwest of Oklahoma City. The serially operated system received about 1 mgd of raw domestic wastewater, and the average cell size was about 6.5 acres. The first two cells were aerated; the third and fourth cells were each stocked with 25,000 two- to four-inch channel catfish; and the fifth and sixth cells each received 750 adult golden shiner minnows. Five pounds of fathead minnows and 175 three-inch Talapia nilotica were stocked in the third cell. Although not stocked, black bullhead catfish, green sunfish, and mosquito fish were present in the system. During a four month period of operation in the summer and early fall, BOD_5 decreased from 184 mg/l in the raw sewage to 6 mg/l in the effluent of the final cell. Suspended solids were reduced from 197 mg/l to 12 mg/l, and volatile suspended solids from 131 mg/l to 6 mg/l.

Bozko et al. (54) found that secondary sewage effluent, subjected to further treatment in ponds containing fish fry, showed a reduction of 20% for total nitrogen and 40% for orthophosphate. Coleman et al. (53) found that total nitrogen decreased from 18.94 mg/l to 2.74 mg/l for the Quail Creek lagoon system. Ammonia nitrogen decreased from 12.67 mg/l to 0.12 mg/l, and organic nitrogen from 6.10 mg/l to 2.17 mg/l. Total phosphorus in the Quail Creek system decreased from 9.0 mg/l in the raw sewage to 2.1 mg/l in the effluent of the sixth pond.

In experiments to grow carp in domestic sewage effluent from the Rye Mead sewage works near Hoddesdon, England, Noble (55) determined that accumulation of mercury in the fish tissue was not a serious problem. Although the bottom mud of the pond contained 1.0 ppm mercury on a dry weight basis, mercury levels in the carp did not exceed 0.02 to 0.04 ppm.

Coleman et al. (53) found that fecal coliform decreased for the Quail Creek system from 3.05×10^6 per 100 ml to 20 per 100 ml. Carpenter et al. (56) analyzed 179 fish and 77 water samples for enteric indicator bacteria and microbial pathogens in the Quail Creek system. While essentially 99.9% of the indicator organisms--total coliforms, fecal coliforms, and fecal strepococci--were removed following passage through the second cell, there remained a low residual of organisms that persisted in the effluent throughout treatment by the sixth and final cell. Tests for the direct isolation of known pathogenic microorganisms revealed three isolates--two enteric bacterial species, and one viral organism--none of which were found in water samples collected past the second treatment cell. No pathogens were found in the fish sampled.

INTEGRATED SYSTEMS

Experimental units that combine several types of organisms rather than focusing on one or two types of organisms for treatment or utilization of municipal wastewater are considered to be integrated systems. Some of these systems are examined in their entirety while others are evaluated on the basis of individual organismal components. Such systems are highly structured and often display complex food chain interrelationships.

Aquatic plants or primary producers which utilize solar radiation to convert nutrients and carbon dioxide to organic matter form the basic population component for all integrated systems. It has been estimated that the maximum photosynthetic production possible for freshwater and marine communities is around 200 metric tons fresh weight per hectare per year (57,58). Direct conversion of all aquatic plants to animal tissue, assuming an efficiency of 15%, would result in a crop of 30 metric tons per hectare per year of herbivores. Further conversion to carnivores could result in a crop of 6 to 12 metric tons per hectare per year. In practice, however, highly enriched culture systems are operated well below their capacity due to the balance that must be achieved between producers and consumers and the changes in rates of metabolic functions associated with major environmental variables.

An excellent discussion is provided by Ryther et al. (58) concerning the factors which influence the development of aquatic populations in highly enriched environments. Relevant items discussed include the processes of population

succession in natural environments as compared to those of highly enriched environments, the problems associated with uncontrolled enrichment of natural systems, and the potential yield of well-managed eutrophic systems. In general, the authors conclude that enriched systems are relatively unstable, failing to develop a fully diversified community and that a high degree of control and management is required to avoid inefficiencies and detrimental effects.

Dinges (28) determined the performance of a 5-step biological treatment system designed to treat effluent from a sewage stabilization pond. The culture unit, 280 feet long and 30 feet wide, was divided into four pond segments by stacked rock barriers. The unit was two feet deep, with the exception of a 900 square foot area 8-foot in depth in the midsection of the second pond. The theoretical detention time for the system was 5.3 days. Water hyacinths, snails, duckweed, scuds, and insects were present in the first pond. The second pond contained zooplankton and duckweed. The third pond contained shrimp and aquatic plants, while the final pond contained fish.

During a five-month period of operation, the integrated freshwater treatment system functioned to achieve significant improvements in water quality. The BOD_3 was reduced from 15 mg/l in the influent to 3.5 mg/l in the effluent, and BOD_{20} from 90 mg/l to 18 mg/l. The reduction in COD concentration was 43% from 70 mg/l to 40 mg/l; suspended solids from 35 mg/l to 7 mg/l or by 75%. Total organic nitrogen decreased from 4.8 mg/l to 1.2 mg/l, and ammonia 95% from 2.1 mg/l to 0.1 mg/l. Fecal coliform and chlorophyll a were reduced by 92% and 99%, respectively.

Extensive research has been conducted at Woods Hole Oceanographic Institition (59-66) directed towards the development of an integrated food chain system for the treatment and/or utilization of secondary sewage effluent mixed with various proportions of seawater. Several food chain combinations have been tested. Among the organisms incorporated in the integrated systems are marine phytoplankton, bivalve mollusks, fin fish, lobsters, polychaete worms, and seaweed. Ryther (59) states, "The dual objectives of the system are to remove nutrients from treated wastewater prior to its discharge to the environment (i.e., a biological tertiary sewage treatment process) and, at the same time grow commercially-valuable crops of shellfish with secondary crops of lobster, flounder, and seaweeds."

Goldman et al. (65) evaluated a prototype process during eleven weeks of summer operation. The system contained marine algae, oysters, and seaweed in series. A mixture of 20% secondarily treated wastewater and 80% filtered seawater was fed to the system. After a significant phytoplankton population developed in the marine algae unit, one half of the pond volume was harvested each day. The hydraulic residence periods for the oyster growth unit and the seaweed growth unit was 1.62 and 0.23 hours, respectively. Efficiency of removal of inorganic nitrogen in the system was 95%, with 45-60% removal for phosphorus. The particulate carbon load was reduced from 4690 µg/min to 686 µg/min by the oyster culture unit, resulting in a removal efficiency of 85.5%.

Ryther (63) developed and evaluated a pilot-plant scale integrated aquaculture system at the Environmental Systems Laboratory of the Woods Hole Oceanographic Institution. The system was composed of continuous flow-through ponds

for the culture of marine phytoplankton and raceways for the culture of shellfish and seaweeds. The American lobster and the winter flounder were stocked in the shellfish raceways to feed on shellfish wastes and dense populations of small invertebrates. Various concentrations of secondary sewage effluents combined with seawater were fed to the system during the first year of operation. Maximum phytoplankton production on an ash-free dry weight basis was 12 g/m^2/day. Mean phytoplankton production was 3 g/m^2/day during the winter, 6 g/m^2/day during the spring and fall, and 9 g/m^2/day during the summer. Maximum seaweed production on an ash-free dry weight basis was 16 g/m^2/day. Mean seaweed production was 3 g/m^2/day during the winter, 5 g/m^2/day during the spring and fall, and 13 g/m^2/day during the summer. During the first year of operation, only limited success was obtained in the culture of shellfish due to poor growth and high mortality.

The mass flow of inorganic nitrogen for the phytoplankton-oyster-seaweed pilot plant system was determined for one month of operation. Total nitrogen removal efficiency including the seawater input and output was 89.3%. When nitrogen values for seawater input and output were subtracted, however, the sewage effluent nitrogen removal efficiency was 93.6%. The maximum nitrogen removal rate was 10.8 lbs/acre/day for the phytoplankton growth unit and the mean annual removal rate was 5.15 lbs/acre/day. The maximum nitrogen removal rate for the seaweed growth unit was 5.4 lbs/acre/day with a mean annual removal of 2.25 lbs/acre/day.

During the second year of operation of the pilot plant system, Ryther (59) found that production and nitrogen removal capacities for the phytoplankton growth unit were similar to those achieved during the first year of evaluation.

Culture experience with the American oyster (Crassostrea virginica) and hard clams (Mercenaria mercenaria) indicated that these organisms have slow growth rates and high mortality. Lack of success utilizing these shellfish species was attributed to inferior and unsuitable food, since the phytoplankton cultures were dominated by the marine algae, Phaeodactylum tricornutum, during most of the year. Recent efforts have been directed toward selection of shellfish species that can readily utilize the dominant phytoplankton species, since growth of more desirable algal species as a food source for the forementioned mollusks has not been achieved.

Two species of seaweed, Neoagardhiella baileyi and Gracilaria foliifera, were evaluated during the second year of operation. Yields exceeded those of earlier studies with a mean annual dry weight of 15 g/m^2/day for N. baileyi and 9 g/m^2/day for G. foliifera. Results obtained from the operation of the seaweed growth unit have been so favorable that experiments are being conducted on seaweed as a one-step culture unit for nutrient removal.

Metcalf (48), in a two-year study of the integrated culture system at the Environmental System Laboratory at Woods Hole Oceanographic Institution, evaluated virus transmission through the aquaculture food chain. Based on results of recovery tests utilizing virus concentration techniques, an average of 1×10^6 plaque forming units (PFU) of enteric viruses were calculated as the daily sewage input into the system during the summer and fall months. The discharge waters of the system were calculated to contain about 1×10^4 PFU of viruses each day for a reduction in virus number of 99%.

ECONOMIC EVALUATION

The major difficulty noted in economic analysis of aquacultural wastewater treatment systems is the lack of verified data regarding design. In most cases efficiency of treatment, production rates, and reliability of the systems being evaluated are not well established. Although design data are based on available published characteristics, estimates of water quality and rates of production are often highly tentative and subject to a number of extrapolation assumptions. More comprehensive and reliable economic evaluations, however, will not be possible until design data are available for operation of aquacultural treatment processes for a broad range of environmental variables, system sizes, and biomass production rates.

Limited economic assessments have been performed for four types of municipal wastewater treatment processes utilizing aquacultural components (10,67-69). Freshwater systems comprising fish, water hyacinths and wetlands, and an integrated marine system composed of phytoplankton, oysters, seaweed, lobsters, and sea worms have been evaluated. The basis for evaluation of the freshwater systems was comparison of costs per unit volume of municipal wastewater to achieve a specified level of treatment. The marine system was evaluated by a comparison of production costs and revenues from sale of organisms with a fixed treatment value assigned per unit volume of municipal wastewater.

Robinson et al. (24) evaluated the performance and costs of a water hyacinth process as tertiary treatment (Table 1) for comparison with other tertiary systems (Table 2). The system design is based on hyacinth ponds which receive 1 mgd of secondary effluent having the following characteristics: 30 mg/l suspended solids, 35.7 mg/l BOD, 21 mg/l nitrogen, and 11 mg/l phosphorus. Treatment costs for the water hyacinth process are based on the construction of a completely new facility rather than the upgrading of existing lagoon facilities. In the cost analysis, it is assumed that final disposition of the harvested water hyacinth entails no costs and produces no revenue.

For purposes of comparing the hyacinth-based with other tertiary wastewater treatment systems, a standard for tertiary effluent was selected having 5 mg/l suspended solids, 5 mg/l BOD, 3 mg/l nitrogen, and 1 mg/l phosphorus. It was concluded that the hybrid design(water hyacinth/chemical system) had a cost advantage in Southern Florida when comparisons were made of those systems that would meet the requirements of the tertiary effluent standards selected. Also noted was the fact that overall cost for the hybrid design could be reduced approximately 20%--to a cost of about 40¢ per 1,000 gallons--by utilizing lagoons already in existence.

Henderson and Wert (67) determined the cost-effectiveness of wastewater aquaculture utilizing fish as an alternative to conventional wastewater systems. The evaluation was oriented toward small municipalities in the Southwestern region of the United States. Costs for 15 wastewater treatment strategies were compared for treating 200,000 gal/day of municipal sewage for a twenty-year period (Table 3). Costs for conventional treatment were adjusted to values given in the Environmental Protection Agency Complete Urban Sewer Cost Index for Dallas, Texas.

Production estimates for stocking several individual species and for polyculture indicated that polyculture provided the greatest fish output (Table 4). Species included were golden shiner, channel catfish, goldfish, bigmouth buffalo, largemouth bass, and bluegill. Estimates of potential values from sale of fish were based on recent published values and direct price quotes (Table 5). Since estimates of revenue for polyculture exceeded those for culturing individual species, the cost effective analysis was based on polyculture for the eleven strategies that contained aquaculture stages.

The efficiency of the 15 strategies, in terms of percentage reduction of pollutants is given in Table 6. A raw sewage influent having 210 mg/l BOD_5, 230 mg/l suspended solids, 11 mg/l total phosphorus, 30 mg/l TKN, and 30 mg/l total nitrogen was assumed.

Based on cost and effectiveness, aquaculture stages in combination with conventional stages appear to provide lower cost alternatives than conventional wastewater treatment systems alone. Henderson and Wert (67) analyzed the cost-effectiveness of the 15 strategies utilizing the multiple objective level approach. The first objective level was compared in terms of BOD_5 and suspended solids (Table 7) while the second objective level was compared for nutrients (Table 8). The authors (67) state, "In all cases when an aquaculture system is capable of achieving a given BOD_5 and SS objective, the aquaculture strategy is the most cost-effective. Not only is the aquaculture the most cost-effective, but in every case the cost differential between the aquaculture strategy and the conventional strategy is substantial. The minimum savings associated with aquaculture are found for objective C, where aquaculture cost are 62 per cent of conventional costs, and the maximum cost saving is achieved for objectives A and B (28 per cent of conventional costs). Under the assumptions of this study there is no aquaculture system that can achieve objective F. However, theoretically, aquaculture systems should be able to reduce all plant nutrients and this limitation of aquaculture probably reflects the methodology of this study plus the lack of knowledge with respect to removal efficiency. Data is unavailable to substantiate this capability of aquaculture. Only stage four . . . of the conventional strategy 12 can reduce BOD_5 and SS to such low levels, and then only at a staggering cost . . . . This, of course, indicates that the potential savings from aquaculture might be massive if future research shows that aquaculture can, in fact, reduce BOD and SS to the levels defined in objective F.

"A similar cost-effective ranking of strategies is obtained when Phosphorus/TKN objectives are employed. . . . Strategy 2, a Waste Stabilization Lagoon with an Aquaculture Lagoon is the most cost-effective strategy for all objectives with the exception of D. Again, data on water quality are insufficient to allow determination of TKN values and, therefore, it is currently unknown, using the methodology employed in this study, whether or not any of the alternative aquaculture systems will meet a TKN $\leq$ 3. Strategy 2 will reduce P to 1.3 mg/l and will thus meet the requirements of objective D, but must be rejected as a result of the TKN unknown. . . . The only strategy that meets those stringent levels of nutrient removal is strategy 12 . . . .

"The cost saving associated with the use of aquaculture relative to conventional methods for nutrient reduction are even more significant than for BOD/suspended

solids reduction. For objectives B & C, the cost of aquaculture represents only 6 percent of the cost of achieving that level of nutrient reduction using the most cost-effective conventional system. This differential is striking and indicates the potential of aquaculture for low cost nutrient reduction."

As a part of the Cypress Wetlands project at the University of Florida, rough cost estimates were made for cypress dome wetland recycling of secondarily treated wastewater (10). Total treatment costs were determined for four rates of sewage effluent input at three pipeline pumping distances. For a 50,000 gpd rate of flow, the total system costs were 26.2, 52.0, and 84.4 cents per 1,000 gallons of sewage at distances of 1, 5, and 10 miles, respectively; for a 500,000 gpd rate of flow, system costs were 9.9, 16.1, and 23.7 cents per 1,000 gallons; 1 mgd rate of flow costs were 8.8, 13.0, and 18.3 cents, and 10 mgd costs were 7.0, 9.6, and 12.8 cents.

Smith and Huguenin (68) performed an economic evaluation of an integrated marine aquaculture system based on the system developed at Woods Hole Oceanographic Institution. Cost comparisons were made for regular heat and free heat, nutrients from secondarily treated sewage effluent and a commercial fertilizer, and several sizes of culture units. Tertiary wastewater treatment was assigned a value of $.17/1,000 gallons. For the largest system, adequate for treating the sewage of a city of about 100,000 people, an economic analysis indicated aquaculture would be profitable if located in a warm climate or if free heat from a power plant effluent could be obtained. Annualized operation costs were $8,841,150 with annual revenues of $12,578,900 for the system having no cost assigned for heat. When a cost was assigned for heat in New England, operating costs of the system became $40,073,230. Only about 5% of the total annual revenue, or $595,000, was assigned as the actual cost for treatment of the wastes.

TABLE 1. PERFORMANCE AND COSTS OF HYACINTH TERTIARY TREATMENT SYSTEMS (1 mgd capacity)*

Area[a], Period[b], Design[c]	Performance				Annualized Cost (¢/1000 gal)
	Suspended Solids (mg/l)	BOD (mg/l)	Nitrogen (mg/l)	Phosphorus (mg/l)	
S. Florida, Full Year Nitrogen Design	5	1.5	1	8	27.1
Other Areas, Growth Period Nitrogen Design	5	1.5	1	8	19.8
Other Areas, Maintenance Per. Nitrogen Design	30	14	11	11	19.8[d]
S. Florida, Full Year Phosphorus Design	5	1.5	1	1	121.6
Other Areas, Growth Period Phosphorus Design	5	1.5	1	1	85.2
Other areas, Maintenance Period, Phosphorus Design	30	14	11	11	85.2[d]
S. Florida, Full Year Hybrid Design	3	1.5	1	0.8	50.4
Other Areas, Growth Period, Hybrid Design	3	1.5	1	0.8	43.1
Other Areas, Maintenance Period, Hybrid Design	3	7-16	11	0.8	43.1[d]

(a) Two regions are considered: (1) southern Florida; and (2) other areas defined as north Florida plus a strip about 100 miles wide along the Gulf Coast.

(b) In southern Florida, it is assumed that growth is year-round and 20 tons/acre-year are harvested. In the other areas, it was assumed that growth occurs only from April through November and 10 tons/acre-year are harvested. The remainder of the year is the "maintenance period".

(c) Three systems were considered: (1) a hyacinth system designed for nitrogen removal-nitrogen design; (2) a hyacinth system designed for removal of both nitrogen and phosphorus-phosphorus design; and (3) a mixed hyacinth/chemical system for removal of both nitrogen and phosphorus-hybrid design.

(d) In the "other areas" cost/1000 gal is computed on an annual basis. Costs are shown as being the same during growth and maintenance periods, even though harvesting costs are not distributed uniformly through the year.

* Taken from Robinson et al. (24), p. 9.

TABLE 2. PERFORMANCE AND COSTS OF COMPETITIVE TERTIARY -TREATMENT SYSTEMS (1 mgd capacity)*

Tertiary System	Performance				Cost (¢/1000 gal)
	Suspended Solids (mg/l)	BOD (mg/l)	Nitrogen (mg/l)	Phosphorus (mg/l)	
Lime Clarification	3	16.4	21	0.8	23.3
Lime Clarification and Multimedia Filtration	0.3	14.5	21	0.8	34.5
Lime Clarification and Ammonia Stripping	3	16.4	2.1	0.8	34.5
Lime Clarification and Ammonia Stripping and Granular Carbon Adsorption	0.3	1.6	2.1	0.8	88.9

* Taken from Robinson et al. (24), p. 9

TABLE 3. ESTIMATED COSTS OF TREATMENT BY STRATEGY AND STAGE*

			Annual Costs $**	¢/1,000 gal
Strategy 1.	Waste Stabilization Lagoon with Aquaculture Raceway			
Stage I	Waste Stabilization Pond	C =	17,433	
		O =	8,500	
		T_1 =	25,933	35.5
Stage II	Aquaculture Raceway	C =	9,660	
		O =	5,877	
		R =	-20,749	
		T_1 =	-5,212	-7.1
			T_2	28.4
Strategy 2.	Waste Stabilization Lagoon with Aquaculture Lagoon			
Stage I	Waste Stabilization Pond	C =	17,433	
		O =	8,500	
		T_1 =	25,933	35.5
Stage II	Aquaculture Lagoon	C =	3,668	
		O =	7,373	
		R =	-20,749	
		T_1 =	-9,708	-13.3
			T_2	22.2

*Adapted from Henderson and Wert (67), pp. 45-9.

** C = 1976 Capital Costs amortized at 5 7/8% for 20 years
O = 1976 Operating Costs
R = Revenues from Aquaculture Component
T_1 = Total Cost of Stage (negative values indicate a revenue)
T_2 = Total Cost of Strategy

(continued)

TABLE 3 (continued)

		Annual Costs	¢/1,000 gal
Strategy 3.	Waste Stabilization Lagoon with Fish		
Stage I	Waste Stabilization Pond	C = 17,433	
		O = 8,500	
		T_1 = 25,933	35.5
Stage I_a	Culture of Fish in Stage I	C = None	
		O = 7,373	
		R = -20,749	
		T_1 = -13,376	-18.3
			T_2 17.2
Strategy 4.	Trickling Filter with Aquaculture Raceway		
Stage I	Primary Treatment	C = 25,355	
		O = 9,567	
		T_1 = 34,922	47.8
Stage II	Trickling Filter and Secondary Sedimentation	C = 34,367	
		O = 12,831	
		T_1 = 47,198	64.7
Stage III	Aquaculture Raceway	C = 9,660	
		O = 5,877	
		R = -10,616	
		T_1 = 4,921	6.7
			T_2 119.2

(continued)

TABLE 3 (continued)

			Annual Costs	¢/1,000 gal
Strategy 5.	Trickling Filter with Aquaculture Lagoon			
Stage I	Primary Treatment	C =	25,355	
		O =	9,567	
		T_1 =	34,922	47.8
Stage II	Trickling Filter and Secondary Sedimentation	C =	34,367	
		O =	12,831	
		T_1 =	47,198	64.7
Stage III	Aquaculture Lagoon	C =	3,668	
		O =	7,373	
		R =	-10,150	
		T_1 =	891	1.2
			T_2	113.7
Strategy 6.	Activated Sludge with Aquaculture Raceway			
Stage I	Primary Treatment	C =	23,698	
		O =	9,359	
		T_1 =	33,057	45.3
Stage II	Activated Sludge	C =	49,087	
		O =	16,142	
		T_1 =	65,229	89.4
Stage III	Aquaculture Raceway			
		C =	9,660	
		O =	5,877	
		R =	-7,342	
		T_1 =	8,195	11.2
			T_2	145.9

(continued)

TABLE 3 (continued)

		Annual Costs		¢/1,000 gal
Strategy 7.	Activated Sludge with Aquaculture Lagoon			
Stage I	Primary Treatment	C =	23,698	
		O =	9,359	
		T_1 =	33,057	45.3
Stage II	Activated Sludge	C =	49,087	
		O =	16,142	
		T_1 =	65,229	89.4
Stage III	Aquaculture Lagoon	C =	3,668	
		O =	7,373	
		R =	-7,151	
		T_1 =	3,890	5.3
			T_2	140.0
Strategy 8.	Activated Sludge-Chemical Addition with Aquaculture Raceway			
Stage I	Primary Treatment	C =	21,537	
		O =	7,858	
		T_1 =	29,395	40.3
Stage II	Activated Sludge with Chemical Addition	C =	54,317	
		O =	17,099	
		T_1 =	71,416	97.8
Stage III	Aquaculture Raceway	C =	9,660	
		O =	5,877	
		R =	-3,185	
		T_1 =	12,352	16.9
			T_2	155.0

(continued)

TABLE 3 (continued)

		Annual Costs		¢/1,000 gal
Strategy 9.	Activated Sludge-Chemical Addition with Aquaculture Lagoon			
Stage I	Primary Treatment	C =	21,537	
		O =	7,858	
		T_1 =	29,395	40.3
Stage II	Activated Sludge with Chemical Addition	C =	54,317	
		O =	17,099	
		T_1 =	71,416	97.8
Stage III	Aquaculture Lagoon	C =	3,668	
		O =	7,373	
		R =	-3,004	
		T_1 =	8,037	11.0
				T_2 149.1
Strategy 10.	Activated Sludge with Denitrification System			
Stage I	Primary Treatment	C =	24,250	
		O =	9,020	
		T_1 =	33,270	45.6
Stage II	Activated Sludge	C =	40,647	
		O =	14,460	
		T_1 =	55,107	75.5
Stage III	Nitrification and Denitrification	C =	44,445	
		O =	18,996	
		T_1 =	63,441	86.9
				T_2 208.0

(continued)

TABLE 3 (continued)

		Annual Costs		¢/1,000 gal
Strategy 11. Activated Sludge with Coagulation Filtration System				
Stage I	Primary Treatment	C =	23,698	
		O =	9,359	
		T_1 =	33,057	45.3
Stage II	Activated Sludge	C =	56,337	
		O =	22,842	
		T_1 =	79,179	108.5
Stage III	Coagulation Filtration	C =	64,984	
		O =	30,660	
		T_1 =	95,644	131.0
			T_2	284.8
Strategy 12. Activated Sludge with Carbon Sorption, Ammonia Removal System				
Stage I	Primary Treatment	C =	23,698	
		O =	9,359	
		T_1 =	33,057	45.3
Stage II	Activated Sludge	C =	56,337	
		O =	22,842	
		T_1 =	79,179	108.5
Stage III	Coagulation Filtration	C =	58,425	
		O =	30,660	
		T_1 =	89,085	122.0
Stage IV	Carbon Sorption	C =	64,984	
		O =	730	
		T_1 =	65,714	90.0
Stage V	Ammonia Removal	C =	2,158	
		O =	17,520	
		T_1 =	19,678	27.0
			T_2	392.8

(continued)

TABLE 3 (continued)

		Annual Costs	¢/1,000 gal
Strategy 13. Extended Aeration with Aquaculture Raceway			
Stage I	Extended Aeration and Secondary Clarification	C = 44,531	
		O = 14,315	
		T_1 = 58,846	80.6
Stage II	Aquaculture Raceway	C = 9,660	
		O = 5,877	
		R = 7,342	
		T_1 = 8,195	11.2
		T_2	91.8
Strategy 14. Extended Aeration with Aquaculture Lagoon			
Stage I	Extended Aeration and Secondary Clarification	C = 44,531	
		O = 14,315	
		T_1 = 58,846	80.6
Stage II	Aquaculture Lagoon	C = 7,373	
		R = -7,153	
		T_1 = 3,888	5.3
		T_2	85.8
Strategy 15. Waste Stabilization Lagoon with Coagulation Filtration			
Stage I.	Waste Stabilization Pond	C = 17,433	
		O = 8,600	
		T_1 = 26,033	35.7
Stage II	Coagulation Filtration	C = 64,984	
		O = 32,294	
		T_1 = 97,278	133.3
		T_2	169.0

TABLE 4. ESTIMATED FISH OUTPUT FROM THE VARIOUS AQUACULTURE STRATEGIES*
(Lbs. per surface acre)**

Treatment Strategy	Poly-culture	Carp	Goldfish	Fathead Minnow	Golden Shiner	Channel Catfish	Buffalo
1	3,695	650	1,355	306	383	1,385	478
2	3,695	650	1,355	306	383	1,385	478
3	3,695	650	1,355	306	383	1,385	478
4	1,752	308	642	145	182	657	227
5	1,695	298	621	140	176	636	220
6	1,232	217	452	102	128	462	159
7	1,201	212	441	100	125	450	150
8	547	96	201	45	57	205	71
9	521	91	192	43	54	195	68
13	1,232	217	452	102	128	462	159
14	1,201	212	441	100	125	450	155

* Taken from Henderson and Wert (67), p. 30

** Anticipated fish production, pounds per surface acre (should be x 6.8 for entire unit for 20,000 gals/day flow)

TABLE 5. ESTIMATED ANNUAL NET REVENUES FROM AQUACULTURE*
(Revenue minus cost of stock)

Strategy	Carp	Buffalo	Channel Catfish	Goldfish	Fathead Minnows	Golden Shiner	Polyculture
1	$653	$578	$20,410	$15,729	$3,309	$4,298	$20,749
2	653	578	20,410	15,729	3,309	4,298	20,749
3	653	578	20,410	15,729	3,309	4,298	20,749
4	310	275	9,682	7,377	1,527	2,002	10,616
5	299	266	9,373	7,126	1,471	1,286	10,150
6	218	192	6,808	5,116	1,045	1,376	7,342
7	213	181	6,630	4,984	1,022	1,342	7,151
8	97	86	3,020	2,128	405	557	3,185
9	91	82	2,874	2,022	382	521	3,004
13	218	192	6,808	5,116	1,045	1,376	7,341
14	213	188	6,630	4,984	1,022	1,342	7,153

* Taken from Henderson and Wert (67), p. 55.

TABLE 6. CUMULATIVE PERCENT REDUCTION OF POLLUTANTS, BY STRATEGY AND STAGE*

Strategy	No. 1		No. 2		No. 3	No. 4			No. 5			No. 6			No. 7		
Stage	I	II	I	II	I	I	II	III	I	II	III	I	II	III	I	II	III
Pollutant																	
BOD_5	81	94	81	94	88	33	86	93	33	86	95	33	90	95	33	90	97
Suspended Solids	59	88	59	88	69	52	85	92	52	85	90	52	89	94	52	89	93
Phosphorus (as P)	55	83	55	88	73	9	18	27	9	18	52	9	27	35	9	27	57
TKN (as N)	67		67			0	3		0	3		0	3		0		
Total N (as N)	63	84	63	86	71	0	0	33	0	0	37	0	0	33	0	0	37

Strategy	No. 8			No. 9			No. 10			No. 11			No. 12					No. 13		No. 14		No. 15	
Stage	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	IV	V	I	II	I	II	I	II
Pollutant																							
BOD_5	33	90	95	33	90	97	33	81	93	33	90	96	33	90	95	98	98	90	95	90	97	81	95
Suspended Solids	52	91	95	52	91	94	52	85	93	52	89	98	52	89	98	99	99	89	94	89	93	59	98
Phosphorus (as P)	9	82	84	9	82	89	9	18	27	9	27	95	9	27	90	93	93	27	35	27	57	55	91
TKN (as N)	0	3		0			0	0	97	0	3	3	0	3	3	3	93	0		0		67	67
Total N (as N)	0	0	33	0	0	37	0	0	90	0	0	0	0	0	0	0	90	0	33	0	37	63	63

*Adapted from Henderson and Wert (67), pp. 69-70.

TABLE 7. COST EFFECTIVE COMPARISON OF SYSTEMS TO ACHIEVE ALTERNATIVE LEVELS OF BOD_5 AND SUSPENDED SOLIDS*

Alternative Objectives mg/l	Aquaculture ¢/1,000 gal	Cost, Aquaculture % of Conventional	Conventional ¢/1,000 gal
Objective A $BOD_5 \leq 30$, $SS \leq 30$	Strategy 2 22.2	28%	Ext. Aeration 80.6
Objective B $BOD_5 \leq 25$, $SS \leq 26$	Strategy 2 22.2	28%	Ext. Aeration 80.6
Objective C $BOD_5 \leq 20$, $SS \leq 22.5$	Strategy 14 85.8	62%	Act. Sludge Chemical Add. 138.1
Objective D $BOD_5 \leq 15$, $SS \leq 19$	Strategy 14 85.8	51%	Coagulation Filtration 169.0
Objective E $BOD_5 \leq 10$, $SS \leq 15$	Strategy 13 91.8	54%	Coagulation Filtration 169.0
Objective F $BOD_5 \leq 5$, $SS \leq 7$	None	--	Carb. Sorp. 365.8

*Adapted from Henderson and Wert (67), p. 60.

TABLE. 8. COST EFFECTIVE COMPARISON OF SYSTEMS TO ACHIEVE ALTERNATIVE OBJECTIVE LEVELS OF PHOSPHORUS AND TKN*

Alternative Objectives mg/l	Aquaculture ¢/1,000 gal	Cost, Aquaculture % of Conventional	Conventional ¢/1,000 gal
Objective A P ≤ 9, TKN ≤ 13	Strategy 2 22.2	63%	Waste Stabilization L. 35.5
Objective B P ≤ 7, TKN ≤ 9	Strategy 2 22.2	6%	Strategy 12 392.8
Objective C P ≤ 5, TKN ≤ 5	Strategy 2 22.2	6%	Strategy 12 392.8
Objective D P ≤ 3, TKN ≤ 3	None	--	Strategy 12 392.8

* Adapted from Henderson and Wert (67), p. 63.
**TKN values for aquaculture are unknown, but always assumed to be less than total N values which are known.

SECTION 4

EVALUATION OF RESEARCH PROGRESS

Of the various parameters selected for evaluation, the majority of information found has been in the areas of organics, solids, and nutrients with a lesser amount of data in the area of biologicals. With few exceptions, the fate and effect of heavy metals and residual hydrocarbons on aquaculture systems has not been adequately investigated.

Of the data reported there is a wide variation with respect to type of system and mode of operation. Table 9 presents selected data reported by various investigators to illustrate this problem. No attempt is made here to analyze differences in operation or other factors which would influence these results. The wide variation in reported results is indicated, however, for the same general type system. Also of significance to this study are the serious omissions in data and the lack of consistency in report

A large portion of the research activity in aquaculture utilizing municipal sewage has emphasized production of organisms rather than treatment of wastewater. In experiments conducted in brackish water ponds fertilized with municipal sewage near Humboldt Bay in Northern California, Allen (70,71) studied survival rates, growth, smolting, and health of salmon. Although the fish culture ponds were reported to have lower total coliform, fecal coliform, and fecal streptococcus counts than an adjacent oxidation pond and creek, the monitoring of other water quality parameters was related to the environmental tolerances of fish populations rather than effectiveness of treatment.

At the New Alchemy East Farm on Cape Cod, Massachusetts, McLarney and Sherman (72) tested environmental variables influencing the production of midge larvae. During the first season of testing Chironomus tentans, culture ponds were fertilized with horse manure; a standing crop of only 11 gm/m^2 (98 lbs/acre) was attained. In subsequent tests following refinement of culture techniques, ponds fertilized with Milorganite® (a sewage sludge-based soil conditioner and fertilizer) has a production rate of 259 gm/m^2 per week (2310 lbs/acre) based on summer and fall observations. Although water quality parameters related to treatment effectiveness were not monitored, production rates are extremely high for herbivores. Assuming a year-round culture capability for midge larvae at the high rate, the annual production would approximate 60 tons per acre.

Many of the experiments involving culture of organisms in municipal wastewater have consisted of either small-scale laboratory experiments or descriptive studies in large systems where only limited control was possible. The research efforts that have been successful from the standpoint of culture capability and

treatment efficiency appear to be those in which the experimental facilities were designed to provide an acceptable environment for the culture organisms. In those cases having inadequate cultural controls or insufficient knowledge of the organisms' requirements, problems usually develop regarding the stability of the process for treatment of municipal wastewater.

Minimal research efforts have been directed toward selective breeding of aquatic organisms. Bardach (50) points out that while many species of terrestrial animals have been subjected to selection with spectacular results, carp and several species of trout are the only aquatic animals over which genetic control has been exercised. Growth rate, fleshiness or muscling, resistance to disease and crowding, and tolerance of temperature variation are among the genetic factors that have been influenced by selective breeding of these aquatic animals.

Animal species for culture in municipal wastewater have been chosen with a view for production of a valuable product as well as treatment of wastewater. Limits in culture capability have contributed to the complexities of obtaining both objectives. Establishing reliable culture techniques for integrated or food chain treatment processes has been particularly difficult. Experiences with the marine phytoplankton-oyster-seaweed process studied at Woods Hole Oceanographic Institution provide a good example of the culture problems encountered in integrated systems designed to remove nitrogen from wastewater, while producing oysters as a primary product and seaweed as a secondary product (59). Although the experimental facility was well designed and contained elaborate environmental control mechanisms, it was not possible for the researchers to maintain a phytoplankton population suitable as a food source for the American oyster. If the major research emphasis becomes production of shellfish, the approach required will be to develop technology for control of the predominating phytoplankton species or, through screening tests, to select a species of shellfish that can utilize the marine phytoplankton occurring naturally. Should nitrogen removal receive the major emphasis, it will involve developmental research for a monoculture seaweed system.

Although a significant amount of information related to municipal wastewater aquaculture is available, perusal of the existing data indicates that discrepancies still exist in certain areas of concern.

TABLE 9. REDUCTIONS OF SELECTED PARAMETERS BY AQUACULTURE SYSTEMS

System Types	BOD (%)	COD (%)	SS (%)	Nitrogen (%)	Phosphorus (%)	Coliform (%)	Reference
Natural Wetlands	80.1	43.7	29.1	41.8	0	86.2	3 6
Artificial Wetlands	95.7 79.7 91.0	86.8 86.9 61.0	87.0	90 60 30-94	91-94 100	90-99.7	12 13 3 14 3
Macrophytes	35.4 81.6 77-97	60.9	84.6 75 71	43.9 50-70	73.6 31.2 60 11 90-97 20-25	96.1 0	28 29 30 31 35 36 32
Invertebrates	69.79 93	67,55	80 83	77	50	99.9 72.1	28,42,43 44 45 42,43
Fish	96.7		93.9	85.5 20	76.7 40	99.9	53 54

REFERENCES

1. Bardach, J. E. et al. 1972. Aquaculture. Wiley & Sons. N. Y.

2. Valiela, I. et al. 1976. Assimilation of Sewage by Wetlands. Paper Presented at the Third Biennial Int. Estuarine Res. Conf., Galveston, Texas.

3. Spangler, F. L. et al. 1976. Wastewater Treatment by Natural and Artificial Marshes. EPA-600/2-76-207, U. S. Environmental Protection Agency, Ada, Oklahoma. 172 pp.

4. Mattson, C. P. et al. 1975. Nitrogen Import and Uptake Measured on Marshes of the Hackensack River in New Jersey. Paper Presented at 38th Ann. Meet. Amer. Soc. Limnol. Oceanogr., Halifax, Nova Scotia.

5. Whigham, D. F. and R. L. Simpson. 1976. The Potential Use of Freshwater Tidal Marshes in the Management of Water Quality in the Delaware River. In Biological Control of Water Pollution, J. Tourbier and R. W. Pierson, Jr., eds. Univ. Pennsylvania, Philadelphia, Pa. pp. 173-186.

6. Greij, E. D. 1976. The Effects of a Marsh on Water Quality. Project Completion Report. OWRT Project Number A-077-Mich. Inst. of Water Res., Michigan State Univ., Lansing, Mi.

7. Drifmeyer, J. E. and W. Odum. 1975. Lead, Zinc, and Manganese in Dredge-Spoil Pond Ecosystems in Virginia. Environ. Conserv. 2: 1-7.

8. Krebs, C. I. et al. 1974. Reduction of Field Populations of Fiddler Crabs by Uptake of Chlorinated Hydrocarbons. Mar. Pollut. Bull. 5: 140-142.

9. Seidel, K. 1976. Macrophytes and Water Purification. In Biological Control of Water Pollution, J. Tourbier and R. W. Pierson, Jr., eds. Univ. of Pennsylvania, Philadelphia, Pa.

10. Cypress Wetlands for Water Management, Recycling and Conservation. 1976. Third Annual Report to National Sci. Found. and the Rockefeller Found. Center for Wetlands, Univ. of Florida, 879 pp.

11. National Science Foundation. 1977. Putting Wetlands to Work. Mosaic 8: 24-29.

12. DeJong, J. 1976. The Purification of Wastewater with the Aid of Rush or Reed Ponds. In Biological Control of Water Pollution, J. Tourbier and R. W. Pierson, Jr., eds. Univ. Pennsylvania, Philadelphia, Pa. pp. 133-137.

13. Small, M. M. 1976. Marsh/Pond System. Data Rpt. Brookhaven Natnl. Lab., Upton, N. Y.

14. Valiela, I. et al. 1973. Nutrient Retention in Salt Marsh Plots Experimentally Fertilized with Sewage Sludge. Estuarine Coastal Mar. Sci. 1: 261-269.

15. Valiela, I. et al. 1975. Production and Dynamics of Salt Marsh Vegetation and the Effect of Experimental Treatment with Sewage Sludge. I. Biomass, Production, and Species Composition. Submitted for Publication in J. Appl. Ecology.

16. Teal, J. M. 1962. Energy Flow in the Salt Marsh Ecosystem of Georgia. Ecology 43: 614-624.

17. VanRaalte, C. D. et al. 1974. Inhibition of Nitrogen Fixation in Salt Marshes Measured by Acetylene Reduction. Estuarine Coastal Mar. Sci. 2: 301-305.

18. Valiela, I. and J. M. Teal. 1974. Nutrient Limitation in Salt Marsh Vegetation. In Ecology of Halophytes, R. J. Reimold and W. H. Queen, ed. Academic Press, New York and London.

19. Valiela, I. and S. Vince. Green Borders of the Sea. Oceanus 19: 10-17.

20. Seidel, K. 1976. Marcophytes and Water Purification. In Biological Control of Water Pollution, J. Tourbier and R. W. Pierson, Jr., eds. Philadelphia, Pa., Univ. Pennsylvania, pp. 109-121.

21. Holm, L. G. et al. 1969. Aquatic Weeds. Sci. 166: 699-709.

22. Penfound, W. T. and T. T. Earle. 1948. The Biology of the Water Hyacinth. Ecol. Monogr. 18: 447-472.

23. Wolverton, B. C. and R. C. McDonald. 1976. Water Hyacinths, Eichhornia crassipes (Mart.) Solms, a Renewable Source of Energy. Proc. Conf. on Capturing the Sun Through Bioconversion, Mar. 10-12, Wash. D. C., Ctr. for Metropolitan Studies.

24. Robinson, A. C. et al. 1976. An Analysis of the Market Potential of Water Hyacinth-Based Systems for Municipal Wastewater Treatment. Battelle Research Report BLC-OA-TFR-76-5, Battelle Columbus Lab., Columbus, Oh.

25. WED Enterprises. 1976. EPCOT Tech. Meet. Sewage Filtration and Energy Production in Using Water Hyacinths. July 1, 1976. Walt Disney World, Orlando, Fl.

26. Bagnell, L. O. et al. 1974. Feed and Fiber from Effluent-Grown Water Hyacinth. In Wastewater Use in the Production of Food and Fiber-Proc. EPA-660/2-74-041, U. S. Environmental Protection Agency, Ada, Ok. pp. 116-141.

27. Wolverton, B. C. et al. 1975. Bio-Conversion of Water Hyacinths into Methane Gas: Part I. NASA Tech. Memorandum X-72725, Natnl. Space Tech. Lab., Bay St. Louis, Ms.

28. Dinges, W. R. 1976. A Proposed Integrated Biological Wastewater Treatment System. In Biological Control of Water Pollution, J. Tourbier and R. W. Pierson, Jr., eds. Philadelphia, Pa., Univ. Pennsylvania, pp. 225-230.

29. Dinges, W. R. 1976. Who Says Sewage Treatment Plants have to be Ugly? Water and Wastes Eng. 13: 20-23.

30. Wolverton, B. C. et al. 1976. Application of Vascular Aquatic Plants for Pollution Removal, Energy, and Food Production in a Biological System. In Biological Control of Water Pollution, J. Tourbier and R. W. Pierson, eds. Philadelphia, Pa., Univ. Pennsylvania, pp. 141-149.

31. Wolverton, B. C. and R. C. McDonald. 1976. Don't Waste Waterweeds. New Scientist 67: 318-320.

32. Wolverton, B. C. and R. C. McDonald. 1976. Water Hyacinths for Upgrading Sewage Lagoons to Meet Advanced Wastewater Treatment Standards: Part II. NASA Tech. Memorandum X-72730, Natnl. Space Tech. Lab., Bay St. Louis, Ms.

33. Wolverton, B. C. and R. C. McDonald. 1975. Water Hyacinths for Upgrading Sewage Lagoons to Meet Advanced Wastewater Treatment Standards: Part I. NASA Tech. Memorandum X-72729, Natnl. Space Tech. Lab., Bay St. Louis, Ms.

34. Ornes, W. H. and D. L. Sutton. 1975. Removal of Phosphorus from Static Sewage Effluent by Water Hyacinth. Hyacinth Control J. 13: 56-58.

35. Sutton, D. L. and W. H. Ornes. 1975. Phosphorus Removal from Static Sewage Effluent Using Duckweed. J. Environ. Qual. 4: 367-370.

36. McNabb, C. D. 1976. The Potential of Submersed Vascular Plants for Reclamation of Wastewater in Temperate Zone Ponds. In Biological Control of Water Pollution. Philadelphia, Pa., Univ. Pennsylvania, pp. 123-132.

37. Wolverton, B. C. and R. C. McDonald. 1975. Water Hyacinths and Alligator Weeds for Removal of Lead and Mercury from Polluted Waters. NASA Tech. Memorandum X-72723, Natnl. Space Tech. Lab., Bay St. Louis, Ms.

38. Wolverton, B. C. 1975. Water Hyacinths for Removal of Cadmium and Nickel from Polluted Waters. NASA Tech. Memorandum X-72721, Natnl. Space Tech. Lab., Bay St. Louis, Ms.

39. Wolverton, B. C. and R. C. McDonald. 1975. Water Hyacinths and Alligator Weeds for Removal of Silver, Cobalt, and Strontium from Polluted Waters. NASA Tech. Memorandum X-72727, Natnl. Space Tech. Lab., Bay St. Louis, Ms.

40. Sutton, D. L. and R. D. Blackburn. 1971. Uptake of Copper by Water Hyacinth. Hyacinth Control J. 9: 18-20.

41. Wolverton, B. C. and M. M. McKown. 1976. Water Hyacinths for Removal of Phenols from Polluted Waters. Aquatic Botany 2: 191-201.

42. Dinges, R. 1973. Ecology of Daphnia in Stabilization Ponds. Texas State Dept. of Health Resources, Austin, Tx., pp. 133-136.

43. Dinges, R. 1974. The Availability of Daphnia for Water Quality Improvement and as Animal Food Source. In Wastewater Use in the Production of Food and Fiber-Proc. EPA-600/2-74-041. U. S. Environmental Protection Agency. pp. 142-161.

44. Frook, D. S. 1974. Clarification of Sewage Treatment Plant Effluent with Daphnia pulex. Thesis, Univ. of Toledo.

45. Trieff, N. M. et al. 1976. Sewage Treatment by Controlled Eutrophication Using Algae and Artemia. In Biological Control of Water Pollution, J. Tourbier and R. W. Pierson, Jr., eds. Philadelphia, Pa.. Univ. Pennsylvania, pp. 231-239.

46. Kerfoot, W. B. and S. A. Jacobs. 1974. Permissible Levels of Heavy Metals in Secondary Effluent for Use in a Combined Sewage Treatment-Marine Aquaculture System I. Monitoring During Pilot Operation. In Wastewater Use in the Production of Food and Fiber-Proc. EPA-600/2-74-041. U. S. Environmental Protection Agency, pp. 65-78.

47. Kerfoot, W. B. and G. A. Redmann. 1974. Permissible Levels of Heavy Metals in Secondary Effluent for Use in a Combined Sewage Treatment-Marine Aquaculture System II. Development of Guidelines by Method of Additions. In Wastewater Use in the Production of Food and Fiber-Proc. EPA-600/2-74-041, U. S. Environmental Protection Agency, pp. 79-101.

48. Metcalf, T. G. 1975. Human Enteric Ciruses in a Waste-Recycling Aquaculture System. Final Report for NSF Grant G. I. 38976. 27p.

49. Tsai, Chu-Fa. 1975. Effects of Sewage Treatment Plant Effluents on Fish: A Literature Review. Chesapeake Res. Consortium Pub. No. 36, Univ. Maryland, pp. 220-229.

50. Bardach, J. E. 1968. Aquaculture. Sci. 161: 1098-1106.

51. Kisskalt, K. and H. Ilzhofer. 1937. Purification of Fish-Pond Water. Arch. Hyg. Bakt. 118: 1-66.

52. Trimberger, J. 1972. Production of Fathead Minnows (Pimephales promelas) in a Municipal Waste Water System. Michigan Dept. of Natural Resources, Fisheries Div., (Mimeographed Rpt.) 5 pp.

53. Coleman, M. S. et al. 1974. Aquaculture as a Means to Achieve Effluent Standards. In Wastewater Use in the Production of Food and Fiber-Proc. EPA-660/2-74-041, U. S. Environmental Protection Agency, pp. 199-214.

54. Bozko, L. et al. 1967. Biological Ponds as the Third Stage of Sewage Treatment. Caz. Woda Sanit. 40: 201-202.

55. Noble, R. 1975. Growing Fish in Sewage. New Scientist 67: 259-261.

56. Carpenter, R. L. et al. 1974. Evauation of Microbial Pathogens in Sewage and Sewage Grown Fish. In Wastewater Use in the Production of Food and Fiber-Proc. EPA-660/2-74-041, U. S. Environmental Protection Agency, Ada, Ok., pp. 46-55.

57. Ryther, J. H. 1959. Potential Productivity of the Sea. Sci. 130: 602-608.

58. Ryther, J. H. et al. 1972. Controlled Eutrophication-Increasing Food Production from the Sea by Recycling Human Wastes. BioScience 22: 144-152.

59. Ryther, J. H. 1976. Marine Polyculture Based on Natural Food Chains and Recycled Wastes. Woods Hole Oceanographic Inst. Tech. Rpt. 76-92, Woods Hole, Ma. (Unpublished Manuscript)

60. Ryther, J. H. 1973. The Use of Flowing Biological Systems in Aquaculture. Sewage Treatment, Pollution Assay, and Food Chain Studies. Woods Hole Oceanographic Inst. Tech. Rpt. 73-2, Woods Hole, Ma. (Unpublished Manuscript)

61. Huguenin, J. E. and J. H. Ryther. Experiences with a Marine Aquaculture Tertiary Sewage Treatment Complex. In Wastewater Use in the Production of Food and Fiber-Proc. EPA-660/2-74-041, pp. 377-386.

62. Ryther, J. H. Microbes as Food in Mariculture. Annu. Rev. Microbiol. 29: 429-443.

63. Ryther, J. H. 1976. Preliminary Results with a Pilot-Plant Waste Recycling-Marine Aquaculture System. In Proc. Int. Conf. on Renovation and Reuse of Wastewater Through Aquatic and Terrestrial Systems. N. Y., Marcel Dekker.

64. Ryther, J. H. et al. 1975. Physical Models of Integrated Waste Recycling-Marine Polyculture Systems. Aquaculture 5: 163-177.

65. Goldman, J. C. et al. 1974. Inorganic Nitrogen Removal in a Combined Tertiary Treatment-Marine Aquaculture System-I. Removal Efficiencies. Water Res. 8: 45-54.

66. Goldman, J. C. and J. H. Ryther. 1976. Waste Reclamation in an Integrated Food Chain System. In Biological Control of Water Pollution, J. Tourbier and R. W. Pierson, eds. Philadelphia, Pa., Univ. Pennsylvania, pp. 197-214.

67. Henderson, U. B. and F. S. Wert. 1976. Economic Assessment of Waste Water Aquaculture Treatment Systems. EPA-600/2-76-293, U. S. Environmental Protection Agency, Ada, Ok., 107 pp.

68. Smith, L. J. and J. E. Huguenin. 1975. The Economics of Wastewater Aquaculture Systems. I.E.E.E. Conf. Record of Engr. in the Ocean Environment. Ocean '75-Sept. 22-24, San Diego, Ca., pp. 285-293.

69. Allen, G. H. 1976. Rearing Pacific Salmon in Saltwater Ponds Fertilized with Domestic Wastewater. Sept. 1974-Nov. 1975 Data Report HSU-SG-10, Humboldt State Univ., Arcata, Ca., 92 pp.

70. Allen, G. H. 1976. Rearing Pacific Salmon in Saltwater Ponds Fertilized with Domestic Wastewater. Oct. 1975-Aug. 1976 Data Report HSU-SG-11, Humboldt State Univ., Arcata, Ca., 99 pp.

71. McLarney, W. and M. Sherman. 1974. Midge Culture at New Alchemy East. Aquaculture and the Fish Farmer. 1: 10-13.